The Effects of Logging and Mass Wasting on Salmonid Spawning Habitat in Streams on the Queen Charlotte Islands

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FISH/FORESTRY INTERACTION PROGRAM

This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multidisciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands forest land base. Originating on steep slopes, many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites.
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides.
- to assess alternative silvicultural treatments for maintaining the improving slope stability.
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests and Lands (Research Branch), and the B.C. Ministry of Environment and Parks (Fisheries Branch). Participating agencies include the Canadian Forestry Service (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

Program results are published through the B.C. Ministry of Forests and Lands, Land Management Report series, as well as in papers presented at symposiums, conferences, and through technical journals.

For information about the program contact Ministry of Forests and Lands, Research Branch, 1450 Government Street, Victoria, B.C. V8W 3E7.

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ABSTRACT

A combination of synoptic surveys and detailed studies was used to assess the effects of logging and mass wasting on salmonid spawning habitats in steepland streams on the Queen Charlotte Islands. Gravel composition was determined at 69 sites in 22 streams using a McNeil gravel sampler to collect 40 Kg samples of gravel at each site for sieve analysis, while gravel stability was measured at 96 sites in 12 streams using vertical erosion monitors. To estimate potential egg losses due to scouring, gravel scour depths were further compared to the vertical distribution of chum and coho salmon eggs in recently completed redds.

Declines in coho egg to fry survival due to logging and/or mass wasting related increases in fine sediment levels are estimated at 15 to 20%. Logging alone accounted for as much of the decline in gravel quality as mass wasting upstream. This indicates that the cumulative impacts of other sediment sources associated with timber harvesting may be at least as great as those caused by a single conspicuous event like a debris torrent upstream. Where logging and mass wasting upstream occurred together there were only slight additional increases in the amount of fine sediments present in spawning gravels. Further increases tended to be obscured by increased gravel scour resulting from large-scale changes in channel morphology. In logged stream reaches directly affected by mass wasting, or in streams where bedloads appeared to be excessive because of mass wasting events upstream, estimated egg losses due to scouring ranged from 66-86% for chum salmon and 45-70% for coho salmon. In other logged but otherwise stable stream reaches with no recent mass wasting, scour related egg loses ranged from 2-14% for chum salmon and 0-4% for coho salmon.

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Ted Harding, with the assistance of Brian Eccles, Dave Davies, and Steve McNaughton, carried out the gravel sampling field program. Sediment composition analyses were completed by Mary Morris. The gravel scour study was assisted by Brian Eccles and Charles Rally. Technical assistance for the egg incubation study was provided by Jim Ellis.

This study was undertaken as part of the Fish/Forestry Interaction Program, an interdisciplinary research program funded by the Government of Canada Department of Fisheries and Oceans, British Columbia Ministry of Forests and Lands and the British Columbia Ministry of Environment and Parks. The Fisheries Employment Bridging Assistance Program made possible the egg incubation study and additional field staff.

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1 INTRODUCTION

In autumn, salmon migrate upstream to spawn in virtually all of the small coastal streams that drain the Queen Charlotte Islands. Pink and chum salmon generally reach only the lowest stream sections before selecting a shallow, gravel-rich site to spawn, while coho salmon and steelhead trout usually seek sites further upstream. To ensure survival, salmon and trout eggs require a clean, well oxygenated gravel environment. To prevent the eggs from being washed away during stormflows and to ensure that alevins (pre-emergent young) can emerge successfully in spring, the spawning gravel must also remain stable and relatively free of fine sediments.

Over the past several decades fishery biologists have directed considerable effort toward measuring the effects of timber harvesting on sediment production in streams and the effects of sediment on fish eggs and alevin survival (Gibbons and Salo 1973; Iwamoto *et al.* 1978; Everest *et al.* 1986). Extensive research has documented that when eroded soil is deposited in streams in large quantities, it can seriously degrade spawning and egg incubation environments. Fine sediments in particular (materials less than 3.36 mm in diameter) can reduce egg survivals by restricting water flow through gravel (Wickett 1958), reducing oxygen concentrations to lethal levels (Alderdice *et al.* 1958), and preventing the removal of toxic metabolic wastes (Rombough1983). Large concentrations of fines in stream gravels can also fill the spaces between the larger particles of high quality spawning gravel and prevent alevins from reaching the surface of the stream (Bjornn 1968; Phillips *et al.* 1975). Studies have also shown that unseasonal surges of fine sediments can reduce the number of benthic organisms inhabiting the stream and ultimately affect fish food availability and fish growth after emergence (Cordone and Kelley 1961; Phillips 1971).

In 1974 and again in 1978, a series of intense multi-day rainstorms hit the Queen Charlotte Islands, triggering large numbers of landslides in logged and unlogged areas. Some events deposited tonnes of eroded material into streams while others sluiced out entire stream sections. Those that moved through the stream channels did so with great force and often scoured the stream to bedrock, removing or redistributing in-channel debris and sediment that had once contributed to the formation of stable spawning habitat. Considerable concern was expressed by both the public and land managers about the effects of logging-related mass wasting on fish habitats and stream productivity. This concern resulted in the Fish/Forestry Interaction Program (FFIP) being initiated in 1981 to examine the effects of mass wasting on streams and forest sites, and to explore ways of mitigating or reducing the number of slope failures attributed to logging (Poulin 1984).

The fisheries studies conducted under FFIP focused on three aspects where mass wasting — primarily debris slides and torrents — could affect the life cycle of juvenile salmonids. The first dealt with describing morphological changes in fish rearing and over-winter habitat attributed to mass wasting (Tripp and Poulin 1986a), while the second involved determining effects on juvenile survival and smolt production (Tripp and Poulin 1987). The last aspect of study, and the subject of this report, was to assess the effects of mass wasting on substrate composition, substrate stability, and salmonid egg to fry survivals in Queen Charlotte streams. In this study, three separate investigations were carried out, including:

1. a synoptic survey of the gravel composition in logged and unlogged streams affected by varying degrees of mass wasting;
2. a survey of the amount of gravel scour occurring in 12 logged streams subjected to various degrees of mass wasting; and
3. an egg incubation study designed to examine coho fry emergence success in upwelling-type incubation boxes containing different concentrations of sand and gravel.

2 STUDY AREA

The Queen Charlotte Islands, located 100 km off the northwest coast of British Columbia just south of the Alaska panhandle, consist of a multitude of islands in a scimitar-shaped archipelago (Fig.1). Moderated by warm Pacific Ocean waters, the Islands' climate is characterized by cool summers, mild winters, strong winds, and high rainfall. Strongly influenced by a diverse topography, mean annual rainfall ranges from 4200 mm at Tasu Sound on the mountainous west coast to 1200 mm in the lowlands on the east coast.

High intensity rain and wind storms can occur anywhere over the island chain, and are one of the dominant factors contributing to landslide activity (Schwab 1983). Most rock formations are deeply jointed, permitting deep penetration of water and rapid weathering well below the surface, and are thus highly susceptible to erosion (Sutherland Brown 1968; Alley and Thomson 1978). Modification of mountain slopes by glaciation has smoothed and oversteepened most hillsides, and produced a thin mantle of noncohesive till that remains as an unstable veneer on many steep sideslopes. Post-glacial mass wasting and gullying is evidenced throughout the mountain and plateau regions by deeply incised hillslopes and gully headscarps which drain directly into first and second order streams.

Mass wasting is a ubiquitous phenomenon across the Queen Charlotte Ranges and Skidegate Plateau. Some 8300 failures have been identified using large scale (1:50000) aerial photography, resulting in an average estimated slope failure frequency of nearly 1.0 per square kilometre over the entire land mass (Gimbarzevsky 1986). Based on an average size of 1.5 ha per failure, Gimbarzevsky's study estimated the total area denuded and hence subject to surface erosion was 12500 ha. Further analysis of slide frequencies from small-scale (1:10000) aerial photography indicated sediment yields in logged areas were 19.8 m^3/ha/year compared to 1.0 m^3/ha/year in unlogged terrain (Rood 1984). These data further indicate that 47% of the total sediment volume produced by mass wasting in logged areas enters streams.

Slope failures occur on the Queen Charlottes in a variety of forms, but probably the most damaging to fish spawning and rearing areas are debris slides and debris torrents that enter gullies or cross valley flats into streams. Debris torrents are particularly damaging because of the great mass of material and momentum built up during these events. Once in motion, debris torrents can sluice out entire stream channels for distances of up to 4 or 5 km (P. Gimbarzevsky, CFS, Victoria, B.C.). Depending upon stream gradient, the terminus of a torrent may stop beyond the mouth of the stream, in which case the channel may remain passable to migrant fish while upstream sections are either scoured to bedrock or buried by colluvium. In larger systems, torrents typically stopped where average channel gradients reached 3.5% (range 1.2-6.2%), frequently forming large impassable debris jams consisting of material scoured from the torrent track (Tripp and Poulin 1986a). In the latter case there is usually no direct damage to habitats downstream, although downstream areas may be exposed later to high quantities of fine sediments mobilized by stream flow from soils originating at the point of failure, eroded stream banks, and in-channel deposits. Further sedimentation downstream results when debris torrent jams inevitably break down and release the large quantities of fine and coarse sediment stored behind them.

The Queen Charlotte Islands are noted for producing nearly 13% of the total provincial escapement of salmon (Pearse 1982) and supporting a highly prized steelhead trout sport fishery. Coho salmon, steelhead and cutthroat trout, and Dolly Varden char are the principal fish species most often directly affected by mass wasting, whereas pink and chum salmon are the species typically found spawning downstream of directly affected reaches. Unlike coho and other rearing species whose juveniles remain in freshwater habitats for 1 or more years before migrating to sea as smolts, pink and chum salmon migrate directly as fry soon after emerging from spawning grounds. For this reason, alterations in rearing habitat quality due to mass wasting have the least impact on pink and chum salmon and the greatest impacts on coho, trout and char. Changes that influence the stability and composition of spawning beds affect all species, but generally have their greatest impact on species like pink and chum salmon. These are the species that prefer to spawn in lower gradient stream reaches where fine-sized sediments have the greatest opportunity to alter gravel composition and the quality of egg incubation environments.

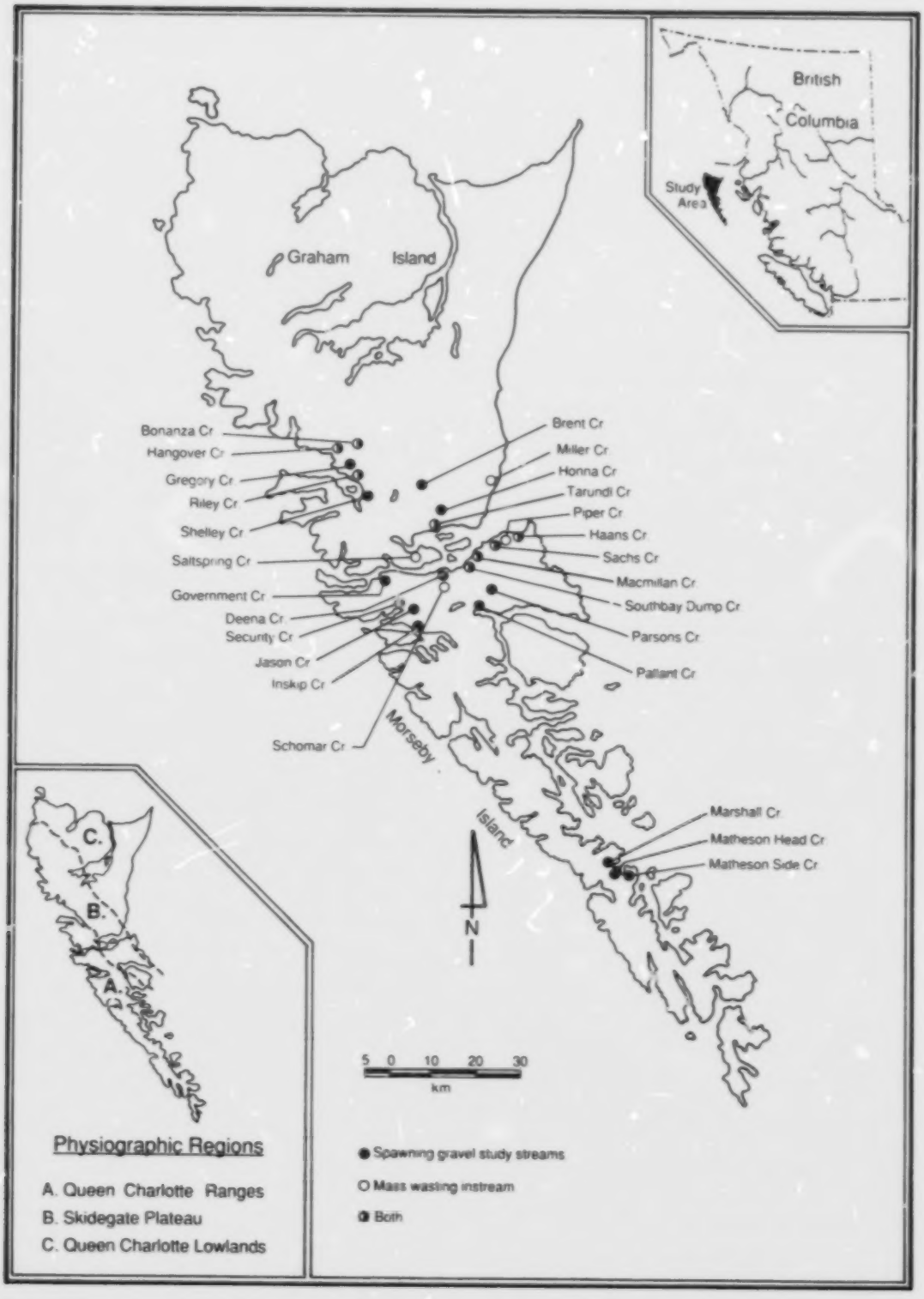


FIGURE 1. Locations of study streams on the Queen Charlotte Islands.

3 METHODS

3.1 Synoptic Spawning Gravel Survey

Between September 18, 1981, and August 17, 1982, a total of 69 samples of spawning gravel were collected from 51 sites in 22 streams (Figure1). Together they exhibited a wide range of logging and mass wasting conditions (Table 1). All sites were sampled at least once during a low flow period between April 1 and October 31, while 16 sites were also sampled during winter between November 1 and March 31. One site (Sachs Creek Site C) was sampled 3 times, once in summer 1981, and again in winter and summer 1982.

3.1.1 Gravel sampling and laboratory analysis

Each site sampled was a pool/riffle break located at the outflow of a pool in a known salmon spawning area. Each sample at each site consisted of two to nine (usually six) separate gravel cores collected with a modified McNeil gravel sampler (McNeil 1962; Tagart 1976). Individually, each gravel core weighed about 6-8 kg. After the gravel composition of the gravel cores taken at each site were analysed, the results were combined to form a single sample of at least 40 kg, the approximate sample weight that sedimentologists feel is required to describe adequately the percentage composition of stream gravels less than 63 mm in diameter (ISO 1977; Church *et al.* 1985).

The McNeil sampler used permitted the extraction of a 15 cm diameter by 25 cm deep gravel core. After the sampler was manually twisted into the streambed, gravel trapped in the central barrel portion of the sampler was removed by hand and placed into a storage basin built around the sampler. Before the sampler was removed, a plunger with a one-way valve was inserted into the barrel and lifted back out once to collect the water and suspended sediments left behind after the gravel was removed. The gravel and water were then transferred to a storage bucket where the sample remained undisturbed for at least a week until sediments suspended in the water had settled out. After settling, the clear supernatant was carefully decanted from the sample which remained in the bucket until analysed.

In the laboratory, each McNeil sample was dried in an oven at a temperature of 200° C, and when dry, passed through a series of 19 sieves. The four largest sieves (75, 63, 50, and 37.5 mm) were agitated by hand, while the next seven (25, 19, 12.5, 9.5, 6.3, 4.75, and 3.36 mm) were sieved into the pan using a Tyler Ro-Tap shaker for 7 minutes. The residue passing 3.35 mm was weighed, and if it exceeded of 500 g, was subsampled with a Tyler SS-50 sample splitter to give a subsample of 500 g or less. This residue was further sieved through an additional 7 sieves (2.36, 1.18, 0.85, 0.6, 0.3, 0.15, and 0.075 mm) for 7 minutes. Sediment retained by each of the 19 sieves was weighed to the nearest 0.1 g on an electronic balance.

Estimated losses in the samples due to handling and transfer between sieves and storage containers were 0.1 % of the total sample weight. A comparison of the total weight passing 3.36 mm to the sum of the weights retained in the seven finer sieves indicated estimated losses of fines due to sieving was about 0.05 %. Dry sieving also introduced a potential source of error because of fine particles sticking to the larger gravels after sieving. To determine the amount of fines retained by the larger gravel fractions, a few samples were dried, sieved, and weighed in the normal manner. Each sieve fraction was then placed in a container and agitated by hand in several centimetres of water, oven dried again, and reweighed. The material in the wash water was dried, weighed, and compared to the difference in the before and after wash weights of the samples. Total changes in the sample weights were less than 0.5 % and the amount of fines washed from the samples less than 0.3 % of the total sample weight.

3.1.2 Data analysis

Gravel composition weights were converted to percents of the total weight which passed through or were retained by each sieve. Preliminary results indicated that the random occurrence of large rocks in the top two sieves resulted in a large variability that was imparted to the rest of the sample. For all subsequent analyses, therefore, these two sieves were deleted from the

TABLE 1. Basin characteristics and spawning areas sampled in the 1981-1982 synopic gravel survey

Stream	Site no(s)	Sample date(s)	Distance(s)[1] upstream (m)	Stream length (km)	Basin area (km²)	% basin logged	Period[2] site(s) logged	Period upper reaches logged	Remarks
Unlogged, No Mass Wasting Upstream									
Bonanza	9	23/09/81	9,100	13.9	47.4	13	Unlogged	Unlogged	Logged gulley systems downstream sluiced out into mainstem 1982, 1983
"	7,9,10	5/04/82	8,975-9,150	"	"	"	"	"	
Gregory	3	16-17/08/82	950	11.1	34.4	4	Unlogged	Unlogged	
Hangover	9	15-16/08/82	200	9.5	21.2	1	Unlogged	Unlogged	Large 155+ year old slide upstream
Insley	1	10/08/82	90-135	6.7	13.7	0	Unlogged	Unlogged	Old slides upstream (undated)
Jason	1,2,3	31/07/82	110-280	4.0	11.9	0	Unlogged	Unlogged	
Marshall Head	1	13-14/08/82	0-100	2.8	2.3	0	Unlogged	Unlogged	
Matheson Side	1,2,3	10/08/82	0-100	3.5	5.0	0	Unlogged	Unlogged	
Security	1,2,3	31/07/82	90-350	18.0	33.9	0	Unlogged	Unlogged	
Unlogged, Mass Wasting Upstream									
Government	1,2	16/11/81	260-370	5.3	16.1	0	Unlogged	Unlogged	Headwaters unstable; many debris torrents (pre-1940, 1972-1978)
"	1,2,3	27/07/82	280-435	"	"	"	"	"	
Matheson Head	1	11/08/82	140	3.8	6.7	0	Unlogged	Unlogged	Headwaters torrented 1979
Logged, No Mass Wasting Upstream									
Brent	1,2	1/08/82	2,300-2,350	9.2	40.3	80	H1981	H1967-82	
Bonanza	1,2	22/09/81	1,630-3,050	13.9	47.4	13	H1975-76	H1975-81	Streambed aggrading; no major mass wasting upstream until 1982
Gregory	1,2	23/09/81	100-250	11.1	36.7	4	H1975	H1974-81	
Hoehn	1	21/10/81	75	14.3	229.5	43	A1956	H1972-82	Slide off sidehill into creek after 1982
Kenny	1	16/12/81	350	18.1	45.0	20	H1964	H1964-81	Main logging road parallels stream
"	"	23/03/82	"	"	"	"	"	H1964-82	
Parsons Trib.	1,2	03/08/82	1,400-1,490	5.1	9.9	41	H1961-69	H1970-78	
Tarundl	1,2,3	21/09/81	250-1,600	6.7	11.0	37	H1964	H1964-82	
"	1,3	22/03/82	250-1,000	"	"	"	"	"	
Logged, Mass Wasting Upstream									
Bonanza	3	5/04/82	7,900	13.9	47.4	13	H1975-77	H1975-82	Debris slides upstream
Deuna	1	19/10/81	1,000	10.3	63.0	35(est.)	H1967	H1966-1981	No mass wasting in mainstem, trib. stream upstream torrented 1978
"	"	19/03/82	"	"	"	"	"	"	
Pelliam	1	07-10/08/82	500	4.4	20.7	55	S1940's	H1950's-69	Banks of major trib. severely eroded, slides, torrents also present
Riley	1	22/09/81	200	11.3	28.7	12	Unlogged	H1973-81	1978-1979 debris torrents upstream
"	2	10/09/81	2,200	"	"	"	H1974	H1973-80	
Sachs	1,2,4	18/09/81	75-2,000	10.6	37.8	62	pre-1956-H74	H1970-81	Upper reaches torrented 1974
"	1,2,4	17/03/82	"	"	"	"	"	H1970-82	
"	3	18/07/82	1,800	"	"	"	H1974	H1970-82	
Logged, Mass Wasting Instream									
Bonanza	4,5,6	28/01/82	8,780-8,900	13.9	47.4	13	H1975-77	H1975-82	1982 debris slide deposition zone
"	4,6	5/04/82	"	"	"	"	"	"	
Macmillan	1	15/10/81	400	4.9	16.2	77	H1946	H1976-1981	Whole stream torrented 1978-1979
Riley	3	18/01/81	3,700	11.3	28.7	12	H1973	H1977-80	1978-79 torrent deposition zone
Shelley	1	22/10/81	300	4.1	5.4	17	H1972	H1972-78	Whole stream torrented 1978
Southbay	1	7/10/81	50	4.1	4.0	82	H1960	H1961-1982	Whole stream torrented 1978; additional torrents 1983, 1985
"	1	18-19/03/82	50	"	"	"	"	"	
"	2	14/10/81	130	"	"	"	"	"	

[1] Distance from stream mouth.

[2] A=A-Frame logging, H=High-lead logging, S=Skidder logging.

subsample and the percent passing data recalculated for the gravel component smaller than 63 mm. Besides reducing the variability, this procedure also allowed a better comparison with the gravel data collected at Carnation Creek. Few particles larger than 63 mm were sampled in Carnation Creek with a freeze core sampler (Scrivener and Brownlee 1982). Percent passing data were calculated for the pooled sample and used to calculate geometric mean particle size (d_g) and sorting coefficients (S_o). The latter, in turn, were used to calculate Fredle values (d_g/S_o), an index of both pore size and gravel permeability that is especially useful in measuring changes in gravel quality resulting from non-point sources of sedimentation (Lotspeich and Everest 1981).

To analyse the data, each site was classified as either logged or unlogged. Unlogged sites (N=21) were those that had no logging immediately adjacent to or anywhere else upstream in the drainage, while logged sites (N=30) were those located within or downstream of logged areas, regardless of when, how, or how much of the drainage was logged. Half of the logged sites sampled were logged between 1956 and 1966 using A-frame, skidder, or highlead cable systems that in almost every case involved extensive cross-stream yarding and falling and the disruption of much of the large woody debris present instream. The remaining half of the logged sites were logged between 1972 and 1982 using more modern highlead cable systems that involved little or no cross-stream yarding and falling, and little or no disruption of the instream debris.

Each site was further classified as having no mass wasting, mass wasting upstream, or mass wasting instream. Mass wasting itself was defined in this study as any debris torrent (or debris torrent-like conditions) that has directly affected a fish-bearing stream channel within the past 10 years, and which are observable on 1:50000 aerial photographs. Sites with mass wasting instream (N=8) included sites that had been directly affected by a debris torrent, while sites with mass wasting upstream (N=13) referred to sites located below stream reaches affected by mass wasting. Sites with no mass wasting (N=30) were sites neither directly affected by debris torrents nor located downstream of debris-torrented sections.

Four analyses of variance (ANOVA) tests were used to compare the data on percent sediment passing 3.36 mm, percent passing 0.85 mm, and Fredle Indices. As illustrated below, all samples collected (N=69) were included in the first two analyses: first (A), with the two logging and three mass wasting categories described above; and second (B), with only two mass wasting categories. (There was no "mass wasting instream" category.) Numbers shown in each cell are the number of samples.

Mass Wasting History

'A'

	None	Upstream	Instream
Unlogged	21	6	0
Logged	16	14	12

'B'

	None	Upstream
Unlogged	21	6
Logged	16	14

'D'

	None	Upstream	Instream
Unlogged	17	4	0
Logged	13	8	7

'C'

	None	Upstream
Unlogged	17	4
Logged	13	8

In the second two analyses (C and D), tests were repeated for a reduced set of sites (N=49) where each site was represented only once. Where sites were resampled in different years, only one sample was chosen so as not to weight the analysis towards those sites. Criteria for choosing sites sampled more than once included using only sites sampled the same year on each stream, and using as many samples as possible from 1982, the year with the most samples. Hence, 1981 sites were accepted in the latter two tests only when there were no sites sampled in 1982 or when most of the sites on a stream were sampled in 1981. When ANOVA tests indicated statistically significant differences, the differences were examined further using simple pairwise t-tests and Mann-Whitney U-tests.

3.2 Gravel Scour Study

Gravel scour was examined in 12 streams, 9 in the Skidegate Inlet region between Graham and Moresby islands, and 3 on the west coast of Graham Island in the Rennell Sound area (Fig.1). As in the synoptic survey of spawning gravels, the study streams were located in watersheds that exhibited a wide range of mass wasting and logging conditions (Table 2). Four of the test sections were in streams that had little or no mass wasting present, either within the reach or upstream (Haans, Miller, Piper, and Tarundl creeks), while four others were in streams that were affected by extensive mass wasting in the form of debris slides or torrents upstream of the test section. These included Bonanza, Hangover, Sachs, and Schomar creeks. The remaining four were in reaches directly affected by debris torrents (Macmillan, Riley, Saltspring, and Southbay Dump creeks). The logging histories of each study reach were equally varied, dating back 40 years (such as in Sachs Creek), while in others only 1 year (as in Hangover Creek). Highlead cable logging was the most widespread method used; however, in at least three study streams (Sachs, Haans, and Piper) parts of the riparian zone had also been logged with A-frames or skidders.

TABLE 2. Basin characteristics of gravel scour study streams

Stream	Stream order	Stream length (km)	Basin area (km^2)	Reach[1] location (m)	Reach length (m)	Reach gradient (%)	% basin logged	Period[2] reach logged	Period upper reaches logged	Mass wasting	Remarks
Bonanza	3°	13.9	47.4	2,600	311	0.9	13	H1975-76	H1975-82	Upstream	1981-82 debris slides, extensive sliding 1983-84
Haans	3°	14.3	29.5	14.0	312	1.0	43	A1956	H1972-83	None	Debris slide upstream 1962-82
Hangover	2°	9.5	21.2	0	400	0.7	-	H1983	Unlogged	Upstream	Stream still eroding and downcutting through 155 year old slide upstream
Macmillan	1°	4.9	6.2	0	680	3.1	77	H1946	H1976-83	Instream	1978-1979 debris torrent
Miller	2°	11.6	22.4	125	660	3.1	3	H1959, 79	H1979	None	Small slides upstream
Piper	1°	14.8	4.2	0	806	2.2	10	A1955	H1976-79	None	Extensive flood damage in summer 1983, channel aggraded
Riley	2°	11.3	28.7	5,600	247	1.5	12	H1974	H1977-80	Instream	1978-79 debris torrent deposition zone
Sachs	3°	10.0	17.8	250	500	0.8	62	A pre-1956	H1974-82	Upstream	1974 debris torrent upstream
Saltspring	2°	3.6	6.3	0	292	3.5	13	H1965	Unlogged	Instream	Debris torrented 1978-79, re-torrented 1981-82, 1983-84
Schomar	2°	3.4	6.6	5	507	2.1	36	H1965-67	H1970-76	Upstream	1978-79 debris torrent, debris jam failure and deposition downstream in 1983-84
Southbay	1°	4.1	4.0	0	260	3.7	82	H1961-68	H1961-80	Instream	Debris torrented 1978-79, extensive flood damage summer 1983, re-torrented 1985
Tarundl	2°	6.7	11.0	1,600	473	4.0	37	H1972-73	H1978-83	None	5m high debris jam at end of reach

[1]Distance from mouth to lower reach boundary.

[2]A=A-Frame logging; H=High lead logging.

3.2.1 Depth of gravel scour

To measure gravel scour, three scour monitors were planted at each of 6-10 sites spaced an average of 60 m apart in each study reach. All sites were pool/riffle boundaries at the tail-end of a pool in stream sections used by spawning salmon. Sudden bends in the stream where the lateral scour characteristics of the two banks were very different were avoided, as were fluvially active sites near recently fallen trees, slumping banks, or bridges. All monitors were planted October 26 to November 14, 1983 and re-examined December 5-11, 1983 (all streams), February 13-23, 1984 (all except Saltspring Creek), and March 11, 1984 (Saltspring Creek).

Scour monitors were similar to those used by McNeil (1962) and Tagart (1976); each consisted of eight 4 cm perforated plastic golf balls strung together on a 1.5 m long monofilament line (100 kg test). The monitors were inserted into the gtavel using a three piece apparatus consisting of a driving rod, inner driver, and an outer standpipe (Fig. 2). The inner driver was made from 3.2 cm diameter stainless steel pipe, 90 cm long and protected with a welded steel hardened tip. With the driver placed inside an outer steel standpipe, the driving rod was used to pound the inner driver and standpipe 40 cm into the substrate. Once in the substrate the inner driver and driving rod were removed, leaving the open standpipe in position. A scour monitor was then dropped into the standpipe and held in place until the outer standpipe was removed, leaving 2 cm of loose gravel on top of the first ball. A plastic disc on the terminal end of the monofilament string prevented the balls from being lost, while a small concrete anchor attached at the other end reduced the chances of the monitors being pulled out by stream flows.

The amount of gravel scour at each monitor site was measured by counting the number of balls exposed overtime: one ball exposed indicated 4 cm of gravel scour, two balls 8 cm of scour, and so on. Where all eight balls plus the anchor were exposed, 38 cm of scour was recorded.

3.2.2 Intragravel permeability and dissolved oxygen concentration

Intragravel permeabilities and dissolved oxygen (D.O.) concentrations were determined at each scour monitor site in the fall (November 3-29) and again in the spring (March 25-31,

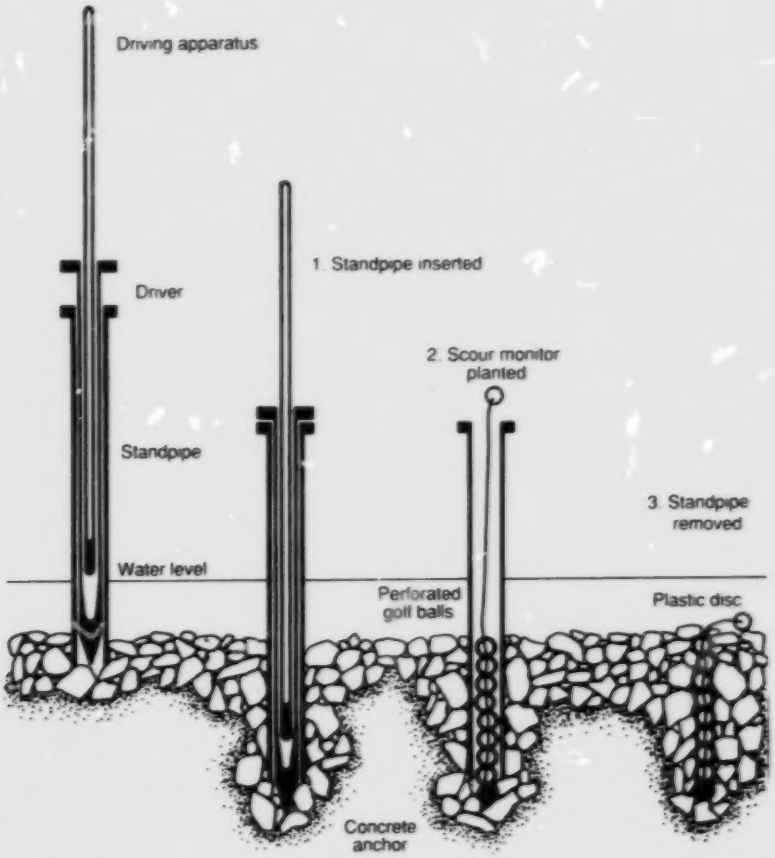


FIGURE 2. Schematic diagram of the scour monitor planting procedure.

1982). Intragravel permeabilities were measured according to Terhune (1958), using a plastic graduated cylinder, a hand-vacuum pump, and a Mark VI standpipe driven 25 cm into the substrate. Water was pumped from the standpipe, held under a 2.5 cm head, and measured in millilitres per second pumped until at least three consistent volumes were obtained. To measure subgravel D.O. concentrations, a stainless steel syringe was used to take a number of 100 ml water samples from a depth of 25 cm (Ryan 1972, in Scrivener and Brownlee 1982). Dissolved oxygen levels were measured to the nearest 0.2 mg/l with a Hach Kit (Model OX-2P) and compared with surface water temperatures and a nomogram (Reid 1961) to determine percent saturation.

3.2.3 Chum and coho egg depth determination

The vertical distribution of chum and coho eggs in recently spawned redds was determined using the same apparatus used to install the scour monitors. This was accomplished by driving the standpipe into redds and pumping the water, sediment, and eggs out from around the end of the standpipe (Fig.3). A 5-cm hole located on the side of the standpipe 40 cm up from the bottom allowed extra water into the pipe when pumping was done at maximum depths; several rows of 3-mm holes spaced between the side-hole and the bottom of the standpipe provided additional water at shallower depths. Depth intervals sampled were 0-5, 10-15, 20-25, 30-35, and 40-45 cm. Water containing the eggs was extracted using a hand-operated bilge pump attached to a 1 m long, 2.5 cm diameter plastic pipe inserted down the standpipe. Pumping time was standardized at 20 seconds. Tests with plastic egg-sized beads indicated this was ample time to extract eggs present at the bottom of the standpipe.

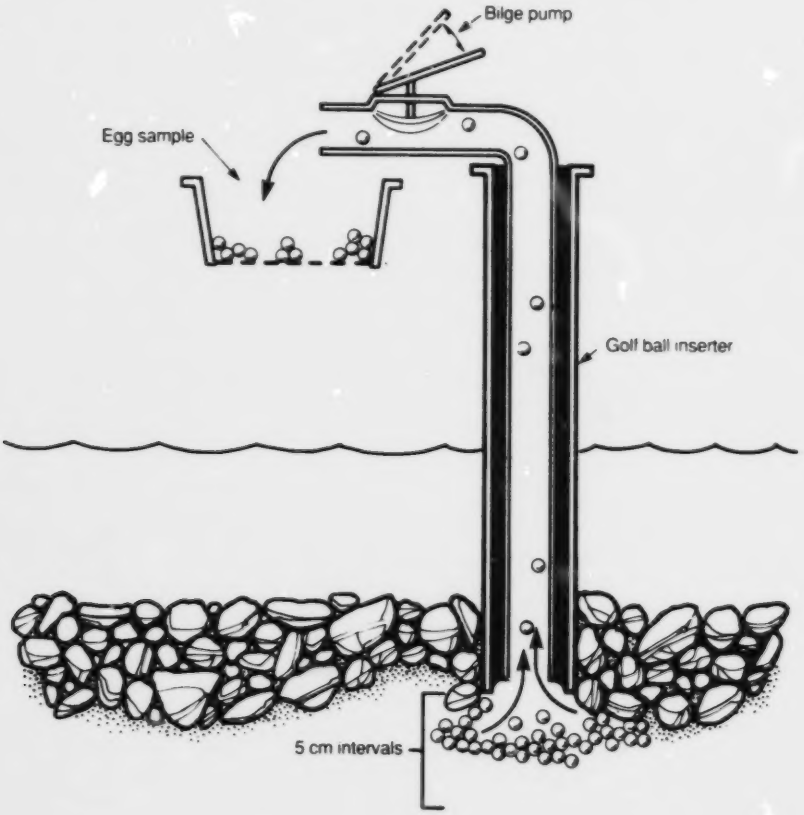
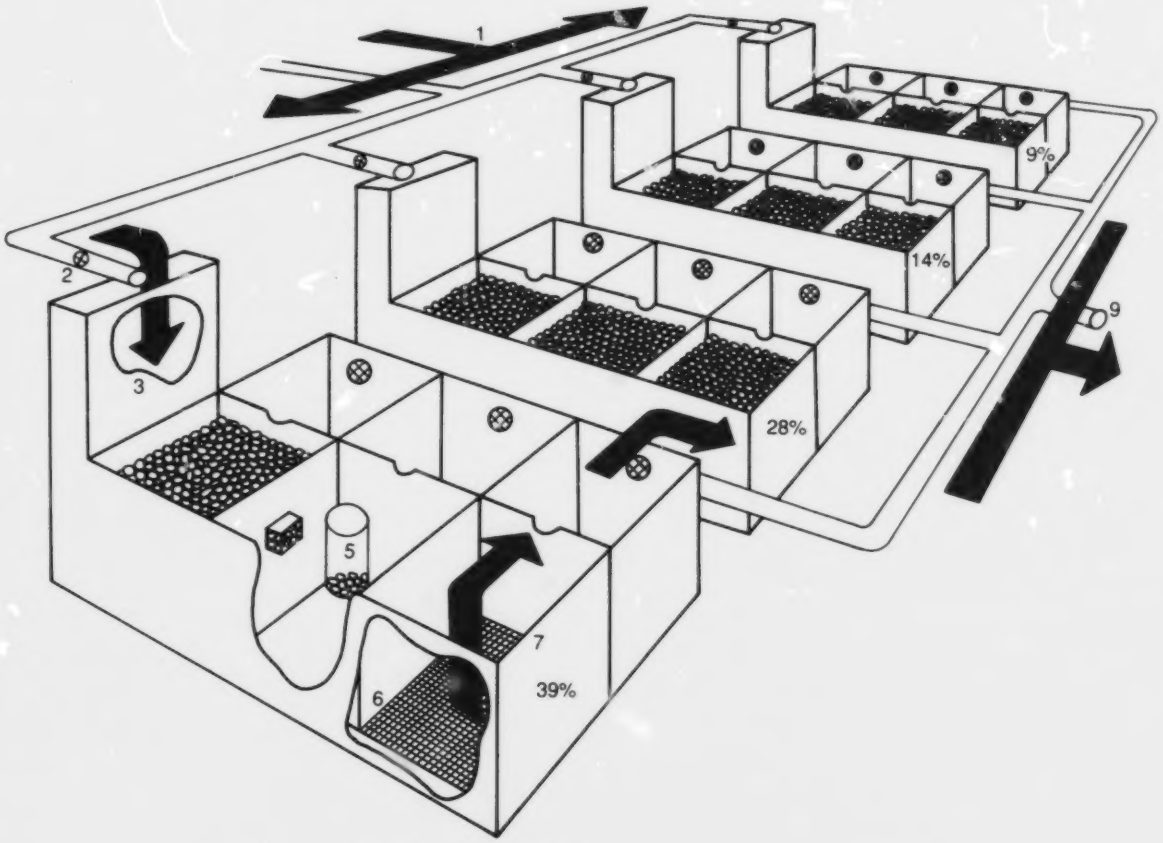


FIGURE 3. Schematic diagram of the egg sampling apparatus showing the hand operated bilge-pump and egg extraction procedure.

3.3 Coho Fry Emergence Study

To assess the effects of different sand concentrations on coho hatching and emergence success, four separate upwelling-type egg incubation boxes (Fig.4) were constructed alongside upper Sachs Creek. Each box (1.83 x 0.61 x 0.61 m) was divided into three compartments (replicates) and filled with gravel containing one of four different concentrations of sand (material <3.36 mm in diameter), ranging from 9 to 14, 28 and 39% by weight, respectively. To prepare each gravel mixture, sand was first sieved out of gravel taken from a dry gravel bar in Sachs Creek and then mixed back into the sieved gravel according to the desired sand concentration. When emergence was completed, the gravel in each compartment was sampled with a McNeil



1. Inflow from water clarifier
2. Flow control valve
3. Header box
4. Vibert box
5. Eyed eggs in test chamber
6. Screening
7. Sand concentration < 3.36 mm
8. Emergence trap with screened outlet
9. Outflow to creek

FIGURE 4. Egg incubation boxes used to assess affects of different sand concentrations (particles <3.36 mm) on coho hatching and emergence success.

sampler and subjected to the sieve analysis described earlier (Table 3).

Eggs for the experiment were obtained from four coho females and fertilized with milt stripped from four males. Eggs were taken in November 1982, and the fertilized eggs incubated in an Akins-type incubation box before planting. On January 20, 1983, a total of 300 eyed eggs were planted in each incubation box compartment using a McNeil sampler to extract a 25 cm deep core from the middle of each compartment. The eggs were placed loose at the bottom of the core and then carefully buried with the gravel removed by the sampler. A Vibert box containing an additional 100 eggs was also buried 15-20 cm down the side of each compartment, as far from the other buried eggs as possible. When fry started emerging from the incubation boxes, the Vibert boxes were carefully pulled out of the gravel and survival to hatching was recorded. Survivals from the eyed stage to emergence were determined for the planted eggs by daily counts of the number of fry present in emergence traps attached to each test compartment. Survival from hatching to the end of emergence (alevin survival) was adjusted for on the basis of survival to hatching in the Vibert boxes.

An upwelling-box design was used to maintain as high a water quality as possible so that egg survivals would not be limited by reductions in intragravel water flow and D.O., or waste product transport. During the experiment, D.O. concentrations in the water entering and leaving each incubation compartment were measured periodically with a Hach Dissolved Oxygen Kit, while water samples for determining subgravel D.O. concentrations were taken with a stainless steel syringe (Ryan 1972, in Scrivener and Brownlee 1982). In the 39% sand compartments, water flows were maintained at a minimum 17 ml/s. In all other compartments the minimum flow was 50 ml/s. Water for the study was taken from a tributary of Sachs Creek and clarified in a 1.8-m^3 settling box prior to use in the incubation boxes. Water temperatures were monitored with Ryan thermographs.

TABLE 3. Composition and characteristics of the sand-gravel mixtures used to assess effects of sand (particles <3.36 mm in diameter, including fines) on coho hatching and emergence success in upwelling-type incubation boxes. Values are mean ± 1SD.

	Sand (<3.35 mm) concentration tested			
	9%	14%	28%	39%
% Fines (<0.85 mm)	3.9±1.7	3.0±1.2	6.5±1.6	7.1±3.1
% Sand (0.85-3.35 mm)	5.2±1.6	11.1±4.0	21.9±0.3	31.9±5.1
% Pea gravel (3.36-9.5 mm)	8.3±2.3	8.0±1.2	7.3±0.3	4.1±1.0
% Medium gravel (9.51-24.9 mm)	13.1±3.5	10.2±3.0	9.9±2.9	4.9±0.5
% Coarse gravel (25.0-62.9 mm)	54.1±5.6	47.1±8.8	44.7±5.8	41.0±2.5
Geometric mean (Dg)	19.9±2.4	16.2±4.5	11.0±1.9	8.4±0.2
Sorting coefficient (S_o)	2.0±0.2	2.2±0.7	4.0±0.3	4.6±0.6
Fredle index (Dg/S_o)	10.1±1.4	8.5±5.6	2.8±0.7	1.9±0.2

4 RESULTS AND DISCUSSION

4.1 Spawning Gravel Composition

4.1.1 Effects of logging and mass wasting

A comparison of the amount of sediment passing 9.50 and 0.85 mm in Queen Charlotte Islands streams and three other river systems in the Pacific Northwest (Tappel and Bjornn 1983; Scrivener and Brownlee 1987) indicate that while some Queen Charlotte streams are among the cleanest recorded, others contain at least as much or higher amounts of fines as other streams (Fig. 5). Overall, the gravel composition of Queen Charlotte streams was most like the gravel in Carnation Creek (Scrivener and Brownlee 1987), but with slightly greater variation in the amount of sediment less than 0.85 mm (fine sand). Logging history aside, the 'cleanest' sites were usually those with no mass wasting in the drainage, or those directly affected by mass wasting. The "dirtiest" sites were usually those located downstream of major mass wasting events.

Two-way ANOVA tests on the full data set (including all replicates taken in different years and seasons at the same sites) showed significant ($P<0.05$) differences in Fredle values and the amount of fines passing 0.85 mm due to mass wasting and logging, but only when logged sites

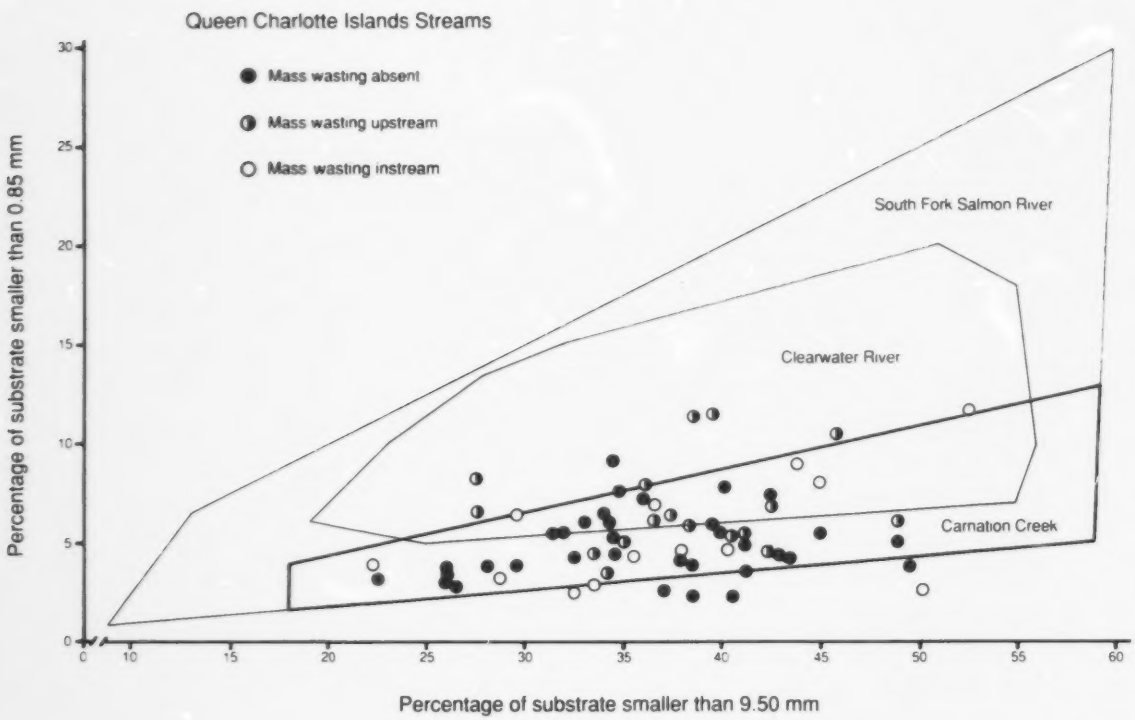


FIGURE 5. Spawning gravel composition in Queen Charlotte Islands streams and three other watersheds in the Pacific Northwest. The polygons for the South Fork Salmon and Clearwater rivers are based on data from 100 and 126 cores respectively (Tappel and Bjornn 1983), while the polygon for Carnation Creek is based on data from 97 cores (Scrivener and Brownlee 1987). Circles are data from 69 sites representing 22 Queen Charlotte Islands streams.

directly affected by mass wasting were deleted from the analysis (Table 4). This occurred because unlogged sites directly affected by mass wasting were never sampled; therefore, deleting the logged sites affected by mass wasting gave a more balanced experimental design (Table 4). When this was done and where no interaction existed among the four remaining ANOVA cells, logging was the main factor influencing the results (P=0.045), followed closely by mass wasting (P=0.053).

TABLE 4. Probabilities of logging or mass wasting having no significant effects at P<0.05, on Fredle indices or the amount of sediment present less than 3.36 mm and 0.85 mm in diameter in Queen Charlotte Islands gravel samples

Analysis	All samples			Same year samples only		
	%Sediment <3.36 mm	%Sediment <0.85 mm	Fredle Index	%Sediment <3.36 mm	%Sediment <0.85 mm	Fredle Index
With debris-torrented sites						
Interaction effects	.066	.862	.041[b]	.730	.372	.432
Treatment effects						
Mass wasting	.513	.008[a]	.123	.060	.005[a]	.043[a]
Logging	.607	.086	.493	.063	.006[a]	.067
Without debris torrented sites						
Interaction effects	.030[b]	.853	.024[b]	.717	.364	.398
Treatment effects						
Mass wasting	.123	.053	.127	.049[a]	.005[a]	.030[a]
Logging	.928	.045[a]	.447	.181	.103	.293

[a] Reject Ho, differences are significant.

[b] Significant interactions between logging and mass wasting, treatment effect tests confounded.

The average amount of fine sediment passing 3.36 and 0.85 mm in the full data set was lowest in unlogged streams with no mass wasting (16.8 and 4.4%, respectively, Table 5),and highest in logged (6.4% passing 0.85 mm) and unlogged (21.1% passing 3.36 mm) streams with mass wasting upstream (Mann-Whitney U tests, P<0.05). The highest mean Fredle value (5.4) indicative of the cleanest gravel was obtained at unlogged sites with no mass wasting or logging upstream. The lowest value (4.0) was obtained at unlogged sites where mass wasting was present upstream (P<0.05), possibly because of the relatively lower sediment transport rates that characterize streams with abundant large organic debris (Beschta 1979; Bilby 1981; Keller and Talley 1979)

Sites directly affected by mass wasting exhibited the highest variability in gravel quality — frequently the cleanest gravel recorded, but often the dirtiest as well. With a mean Fredle value of 4.7, sites directly affected by mass wasting had the second highest average Fredle value recorded. In these reaches, Fredle values ranged from 8.9 in Southbay Dump Creek, three winters after a debris torrent, to 2.0 in Bonanza Creek just 2 weeks after torrenting. Differences in the length of time elapsed and therefore the amount of sediment flushed out after mass wasting

TABLE 5. Amount of sediment passing 3.36 and 0.85 mm and Fredle indices in gravel samples collected from logged and unlogged streams on the Queen Charlotte Islands, with and without mass wasting. Data based on all sites sampled over the course of the study (N=69); values are means ± 1SD.

Logging history	Mass wasting history	No. sites	Mean % passing 3.36mm	Mean % passing 0.85mm	Fredle Index
Unlogged	None	21	16.8±3.8	4.4±1.5	5.41±1.58
	Upstream	6	21.1±5.0	5.6±1.7	4.00±1.13
Logged	None	16	19.2±2.2	5.4±1.7	4.29±0.56
	Upstream	14	18.4±4.9	6.4±2.4	4.57±1.23
	Instream	12	19.6±7.3	5.1±2.5	4.77±1.92

but before sampling, appeared to account for a substantial amount of the variation. As discussed later in this report, stream gradient and the degree of gravel scour also tended to be higher at sites directly affected by debris torrents, further increasing the variability in the data.

Eliminating replicate samples taken at the same site in different years or seasons provided a reduced, but less variable data set with a much clearer pattern overall (Table 4). In the reduced data set, all three variables tested (Fredle indices, % passing 3.36 and 0.85 mm) were either significantly affected by mass wasting or close to it (P=0.003-0.088). As with the full data set, this was particularly true when sites directly affected by mass wasting were removed from the analysis to achieve a balanced study design with no empty cells. When there were no interactions between the four remaining ANOVA cells, the data indicated that logging and mass wasting both have a significant influence on the data ($P<0.05$). Logging appears to have its greatest effect on sediments less than 0.85 mm in diameter, while mass wasting appears to have its greatest effect on the larger sediments less than 3.36 mm in diameter.

In the reduced data set, sites directly affected by mass wasting had the cleanest gravel overall, both in regard to percent passing and Fredle values (Table 6). This can be attributed to the

TABLE 6. Amount of sediment passing 3.36 and 0.85 mm and Fredle indices in samples collected from logged and unlogged streams on the Queen Charlotte Islands with and without mass wasting. Data based only on sites sampled in 1 year (1981 or 1982, N=49); values are means ±1SD.

Logging history	Mass wasting history	No. sites	Mean % passing 3.36 mm	Mean % passing 0.85 mm	Fredle Index
Unlogged	None	17	16.7±3.9	4.3±1.5	5.40±1.63
	Upstream	4	18.9±4.6	4.6±1.1	4.48±1.08
Logged	None	13	19.2±2.3	5.6±1.8	4.31±0.6
	Upstream	8	20.5±3.8	7.1±2.2	4.15±1.12
	Instream	7	16.3±4.7	3.9±1.9	5.54±1.84

removal of fines by excessive gravel scouring (see Section 4.2.1). The next cleanest sites were, in order, unlogged streams with no mass wasting upstream, unlogged streams with mass wasting upstream, and logged streams with no mass wasting upstream. Significantly, logging alone had a greater impact than mass wasting alone on the amount of fine sediment present. Logged streams with mass wasting upstream contained the highest concentration of fines. Compared to unlogged streams with no mass wasting, the average amount of sediment passing 0.85 mm in logged streams with mass wasting upstream increased from 4.3 to 7.1%, for a net difference of 65% (Mann-Whitney U tests, $P<0.05$). The average amount of sediment passing 3.36 mm increased from 16.7 to 20.5%, for a net difference of approximately 23% ($P<0.05$). Fredle values also declined from an average of 5.4 (indicating relatively clean gravel) in unlogged, non-mass wasted streams to 4.1 (indicating relatively dirty gravel) at logged sites with mass wasting upstream, a net decline of 23% ($P<0.05$).

4.1.2 Potential impacts on egg to fry survival

The Fredle values determined for each sampling site were converted to estimates of coho survival to emergence using two different relationships (Table 7). The first of these was developed by Lotspeich and Everest (1981) from results of an experimental trough study on coho conducted by Phillips *et al.* (1975). The second was developed by Scrivener and Brownlee (1987) for coho at Carnation Creek. Using Lotspeich and Everest's relationship, the estimated decline in coho egg survival attributed to logging and/or mass wasting upstream was 8-11%, while Scrivener and Brownlee's relationship suggests a slightly greater decline, 15-20%. Of the two estimates, those based on the Carnation Creek data are probably the most accurate because they are based on actual long-term survival data from egg deposition to emergence in a natural stream environment. They thus take into account such factors as site selection by adult fish, the cleaning action that occurs during redd construction, variation in stream flows, and variation in intragravel permeabilities and D.O. through the entire incubation period. The estimates based on Lotspeich and Everest's (1981) relationship are probably low because they include only the latter part of the incubation period (from the alevin stage to emergence) in troughs.

TABLE 7. Estimated coho egg to fry survivals in Queen Charlotte Islands streams based on coho egg to fry survival relationships from Lotspeich and Everest (1981) and Scrivener and Brownlee (1987)

				Predicted coho survivals (%)	
Logging history	Mass wasting history	No. sites	Mean Fredle Index	Lotspeich & Everest (1981)	Scrivener & Brownlee (1987)
Unlogged	None	17	5.40	67	56
	Upstream	4	4.48	59	41
Logged	None	13	4.31	58	38
	Upstream	8	4.15	56	36
	Instream	7	5.54	68	57

Coho embryo survivals were not determined in this study nor are any data available for the Queen Charlotte Islands. To estimate the decline in embryo survival attributable to sedimentation from mass wasting and logging, the relationships developed by Scrivener and Brownlee (1987) were used. Based on their relationships and using the Fredle index obtained for unlogged

streams with no mass wasting (Figs.5 and 4), estimated maximum fry survival in unaffected streams would be 56%. At 56%, a further 15-20% decline in survival (down to 36-41%) due to mass wasting and logging-related sedimentation could represent a net reduction in natural survival levels of 27-37%.

Because the gravel composition data for this study are based only on gravels found in the upper 25 cm of the stream bed, 56% is probably too high an estimate of egg to fry survival in unaffected Queen Charlotte streams. The reason for this is that the relationships developed for coho at Carnation Creek are based on the lower half of freeze core samples, representing the 15-30 cm depth interval. Scrivener and Brownlee (1982) have shown that sand and fine sediments increase significantly with depth, which results in decreased Fredle values and fish embryo survival (Scrivener and Brownlee 1987). Since the same stratification no doubt occurs in Queen Charlotte streams, the Fredle values obtained with the McNeil sampler are probably high. The depth of egg deposition data in this study (See Section 4.2.2) further indicate that chum and coho salmon on the Queen Charlottes deposit their eggs at depths considerably lower than the average depth measured during gravel sampling. Mean average egg depth for these species was measured at 25 and 29 cm, respectively.

The coho egg to fry survival estimates derived at Queen Carnation Creek for the prelogging period are probably better estimates of the egg to fry survivals in unaffected Charlotte streams. Coho egg to fry survivals before logging at Carnation Creek ranged from 23 to 36% (Scrivener and Brownlee 1982). Based on these values, a further reduction of 15-20% (down to 3-12%) represents a potential 41-87% decline in survival attributable to increases in mass wasting and/or logging-related sedimentation. These impacts would be largely imposed on pink and chum salmon because freshwater production for these species is more directly related to the number of recently emerged outmigrant fry produced, and hence the quality of the incubation environment. Coho and steelhead production, in contrast, is usually limited more by the amount of freshwater rearing and over-winter habitat available, and less by fluctuations in fry abundance levels (Bustard and Narver 1975; Tschaplinski and Hartman 1983; Heifetz *et al.* 1986)--so long as adult escapements remain high and streams are adequately seeded (Cederholm *et al.* 1981).

4.2 Gravel Scour

Mass movements into channels vastly increase the sediment loading in streams, and, as such, radically alter the ability of natural hydraulic controls like large organic debris (LOD) to stabilize bedload and gravel movement. Once mobilized, material introduced into streams is subject to intense fluvial action from scouring in both depositional and sediment transport zones. When scouring occurs in spawning areas, egg loss is assumed to be related directly to depth of scour and the depth at which eggs are deposited.

4.2.1 Gravel scour attributed to mass wasting

All the streams included in this study were logged, but exhibited a range of mass wasting from none to mass wasting within or upstream of each study reach. Debris-torrented streams were considered the most seriously affected streams and included Macmillan, Saltspring, and South Bay creeks. These streams were also characterized as having the highest gradients. They were followed next by three streams from the Rennell Sound area which, on the basis of (1)thalweg profiles in the lower reaches (Hogan 1986), (2)the presence of extensive gravel bars, (3)a small average surface substrate size, and (4)widespread dewatering during low flow periods, appeared to be aggrading sediments as a result of natural (Hangover Creek) or logging-related mass wasting upstream (Bonanza and Riley creeks). The most stable reaches examined were located in the low-gradient sections of Sachs and Haans creeks, followed next by the relatively high-gradient sections of Miller and Tarundl creeks. Piper Creek, a small moderate-to low-gradient stream, was considered to be of only intermediate stability because of extensive damage and sediment aggradation resulting from major flooding the previous summer. Similarly, Schomar Creek was also thought to be of intermediate stability because of large volumes of sediment passing through a break in a debris torrent jam perched just above the study reach.

The greatest amount of scour occurred in streams with the greatest degree of mass wasting and the highest gradients (Table 8). The average scour depth recorded for the three debris-torrented streams in the central Skidegate Inlet region was 17 cm by mid-winter (range 2-25 cm) and 33 cm by the end of winter (range 27-35 cm). In streams where bedload appeared to be aggrading as a result of mass wasting upstream (i.e., the Rennell Sound streams), the average scour was only 1 cm in mid-winter, but increased to an average of 28 cm (range 24-33 cm) by the end of winter because of intense flooding from late winter storms. The least active stream reaches

TABLE 8. Depth of gravel scour (cm) in selected Queen Charlotte Islands streams, December 5, 1983, to March 11, 1984

		Mid-winter			Post-winter		
Stream	Stream description	Date	N	x Depth (cm) ±1SD	Date	N	x Depth(cm) ±1SD
Haans	Skidegate Inlet,	Dec.8	17	0.7±2.1	Feb.13	17	2.1±3.5
Sachs	low gradient,	Dec.8	18	4.2±5.6	Feb.16	18	7.3±8.4
	no recent		35	2.5±4.6		35	4.8±6.9
	disturbances						
Miller	Skidegate Inlet,	Dec.9	18	5.2±6.5	Feb.13	18	13.4±16.1
Tarundl	high gradient,	Dec.9	27	5.5±6.5	Feb.23	27	14.9±11.8
	no recent		45	5.4±6.4		45	14.4±13.5
	disturbances						
Schoman	Skidegate Inlet,	Dec.7	25	1.3±1.9	Feb.23	26	21.7±15.5
Piper	mod. gradient,	Dec.8	30	16.7±14.1	Feb.16	30	20.8±14.1
	recent floods		55	9.7±13.0		56	21.0±14.6
	and debris jam failures						
Bonanza	Rennel Sound,	Dec.5	18	1.8±5.2	Feb.22	18	33.1±19.2
Hangover	low gradient,	Dec.6	18	0.0±0.0	Feb.22	18	28.7±15.0
Riley	mass wasting	Dec.5	18	1.3±2.7	Feb.23	18	23.8±14.9
	upstream,		54	1.0±3.4		54	27.0±14.7
	gravel aggrading downstream						
Macmillan	Skidegate Inlet,	Dec.8	30	24.6±13.4	Feb.23	30	27.3±13.1
Saltspring		Dec.11	30	1.9±3.9	Mar.11	30	34.0±10.5
Southbay	high gradient,	Dec.7	30	24.7±16.3	Feb.21	30	35.2±13.2
	debris-torrented		90	17.1±16.3		90	31.3±11.5

(Haans and Sachs creeks) averaged only 5 cm of scour by the end of winter (range 2-7 cm), a value 5-7 times lower than the most active reaches.

The scour results indicate there can be substantial scouring in Queen Charlotte Islands streams, particularly in those that have been torrented or which were transporting excessive amounts of sediment as a result of bank destabilization or upstream slides and torrents. Not all gravel scouring occurred in the same manner, however. In debris-torrented streams where much of the in-channel debris had been removed or rendered ineffective for stabilizing bedload, scour was largely a result of the entire streambed shifting, with little net change in bed elevation throughout the study reach. In aggrading streams where LOD was still abundant, the scour recorded was due more to scouring where new trees had fallen into the creek or where large organic debris had shifted position instream.

In the absence of stream flow data for local rainfall records, we have no idea how representative the scour depths recorded in this study are of scour in other years. Conditions that prevailed during the study year, however, suggest it was a reasonably active year on the west coast. As a result, the scour observed there was probably greater than average. In January 1984, one storm on the west coast caused Bonanza Creek to overtop its banks and inundate a significant portion of of the valley flat. This same storm also triggered 13 landslides in the Bonanza Creek basin, 4 of which ended up in Bonanza Creek. On the east coast, rainfall records at Sandspit suggest that stream flows were also active during the study period, but not excessively so. Thus, the scour observed on the east coast may be more representative of average scour conditions. While total monthly precipitation at Sandspit significantly exceeded the thirty year average in three out of five winter months (October-February, 30-year normals, Atmospheric Environment Service, Environment Canada), only in February was the 24 hour maximum rainfall significantly greater than average, with an estimated return period of just over 2 years.

4.2.2 Vertical distribution of chum and coho eggs

To estimate the potential loss of salmon eggs due to gravel scour, the depth of egg deposition was determined at recent completed redds of chum and coho salmon. Results of the egg depth measurements indicated that chum salmon eggs were almost normally distributed from the surface of the streambed to a depth of 40-45 cm (Fig.6), with the highest number of eggs

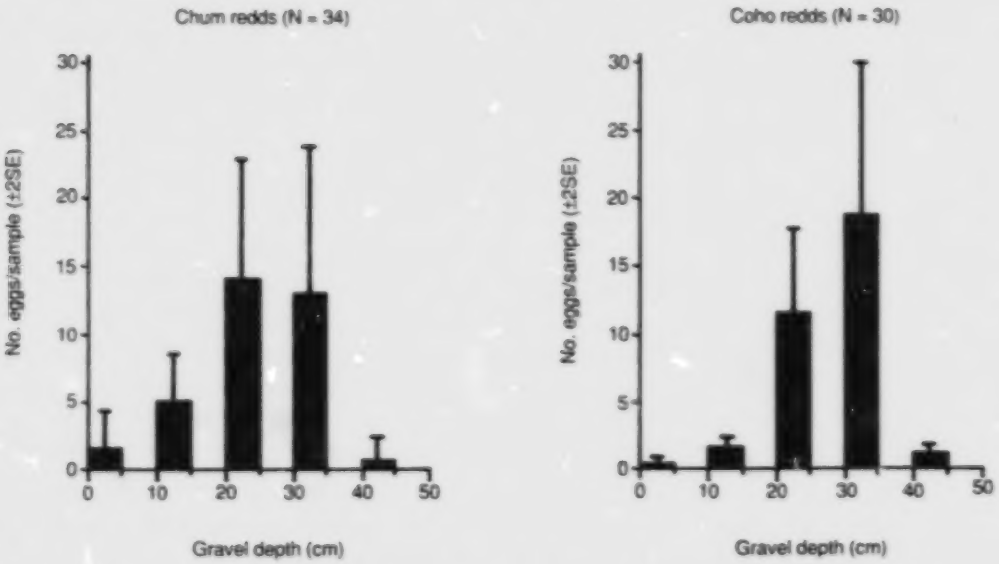


FIGURE 6. Vertical distribution of chum and coho salmon eggs in recently spawned redds on the Queen Charlotte Islands.

(13.6 ± 9.4 eggs per sample, 2 SE) being 20-25 cm below the surface. Coho eggs by comparison (Fig. 6) were deeper, with the highest numbers (18.3 ± 12.0 eggs per sample, 2SE) being 30-35 cm below the surface. Adult coho females on the Queen Charlotte Islands tend to be larger in size than adult chum females according to (L. Orman, pers. comm., DFO File Data, Prince Rupert, B.C.), a factor which probably accounts for the greater depth of coho eggs. In other studies, van den Berghe and Gross (1984) reported a strong, positive correlation between female size and nest depth, with nest depths ranging between 9 and 27 cm for females 46.5 and 74 cm long (fork length), respectively. In still other studies, Koski (1966) reported coho eggs between 18 and 28 cm in two excavated redds, while McNeil (1962) indicated that pink salmon covered their eggs with 8-38 cm of gravel, resulting in an average egg depth of 22.3 cm.

The egg depth data were used to establish egg loss to scour depth relationships for pink, chum, and coho salmon (Fig. 7). The curves summarize the proportion of each species' eggs present above any given depth. The chum and coho salmon curves were derived by measuring the area under successive portions of a line connecting the mean egg densities recorded for each depth interval given in Figure 6. The results indicate that the mean egg depth was 25 cm for chum and 29 cm for coho salmon. Pink salmon eggs were not sampled during the study, but to develop an approximate scour-depth relationship for this species we established 20 cm as the mean egg depth for pink eggs in this study (after Klassen 1984) and an egg distribution pattern that was the mirror image of the pattern exhibited by coho were established.

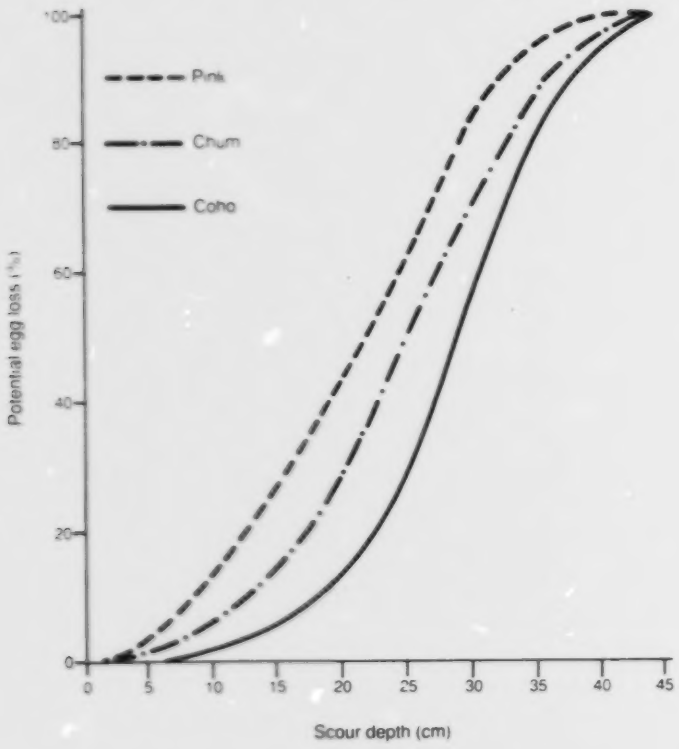


FIGURE 7. Potential egg loss/scour depth relationships for pink, chum and coho salmon on the Queen Charlotte Islands. Curves for chum and coho salmon are based on a mean egg depth of 20 cm (from Klassen 1984).

4.2.3 Potential egg losses due to scouring

Potential egg losses due to scouring were estimated by comparing the average depth of scour in each study reach with the proportion of each species' eggs present above average scour depth. By mid-winter, the potential egg losses in stream sections with little or no mass wasting were relatively low, averaging 0-10 % for pinks, 0-5 % for chums, and 0-1 % for coho. Debris-torrented streams in contrast averaged 34, 19 and 8 % for pink, chum, and coho salmon, respectively, over the same time period. In the most extreme case (Southbay Dump Creek), estimated egg losses for the three species were 65, 50 and 30 %, respectively.

By the end of winter, estimated egg losses due to scour were substantial in all streams except the low-gradient study sections not directly affected by mass wasting (Fig. 8). At the low- to high-gradient sites with no mass wasting (Haans, Sachs, Tarundl, and Miller creeks), average potential egg losses ranged from 4 to 26 % for pink salmon and from 0 to 4% for coho salmon. In torrented streams (Macmillan, Saltspring, and South Bay creeks) and in those where the bedload was considered to be excessive (the Rennell Sound streams), estimated egg losses ranged from 80 to 96 % for pink, 66 to 86 % for chum, and 45 to 70 % for coho salmon.

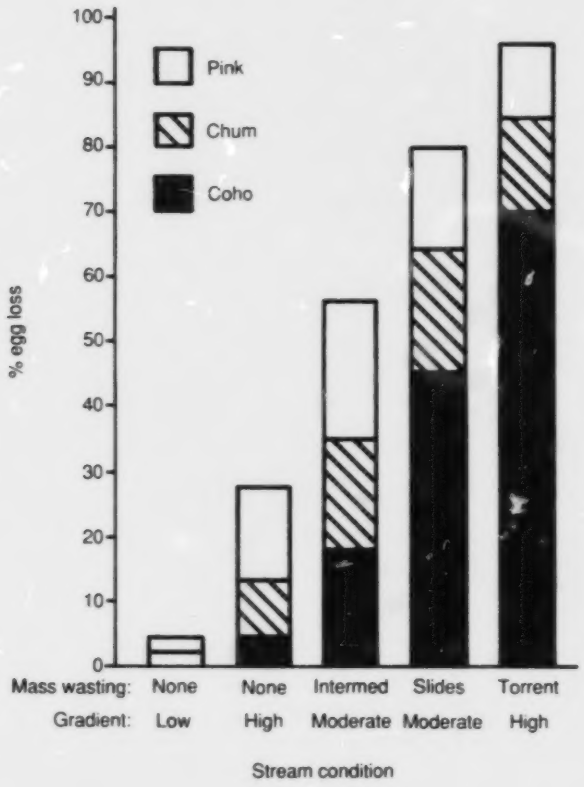


FIGURE 8. Projected post-winter egg losses due to gravel scouring at salmon spawning sites on the Queen Charlotte Islands, October 26, 1983 to March 11, 1984.

4.2.4 Intragravel permeability and dissolved oxygen concentration

Gravel permeability (in millilitres per second) declined from fall to spring in 6 of the 12 scour study streams, 2 of which (Haans and Sachs creeks) had the lowest amount of scour recorded over winter and three (Macmillan, Saltspring, and Southbay Dump Creeks — all debris-torrented streams) the highest degree of scour (Table 9). Only in Haans Creek were the differences significant. In all other streams, permeability increased over the winter, significantly so in the case of Bonanza Creek.

Subgravel D.O. levels in all streams increased over-winter from a mean average of 6.0 mg/L (range 5.5-7.1) to 6.9 mg/L (range 6.2-7.7, $P<0.05$). Similarly, subgravel percentage D.O. saturation also increased significantly ($P<0.05$) over-winter from a mean average of 48.5% (range 44.0-57.5%) to 53.7% (range 48.0-59.0%). Essentially the same values and seasonal differences were also reported for Carnation Creek (Scrivener and Brownlee 1982).

TABLE 9. Mean permeability, dissolved oxygen concentration (±1SD), and average percent oxygen saturation at scour monitor sites in the fall (November 3-29, 1983), and spring (March 25-31, 1984)

		Permeability (mL/s)		D.O. (mg/L)		% Oxygen saturation	
Stream	N	Fall	Spring	Fall	Spring	Fall	Spring
Haans	17	43.1±16.5[a]	28.8±24.3	5.7±1.1	6.3±1.1	46.0	49.0
Sachs	18	33.0±22.6	27.6±22.8	5.6±1.0	6.2±0.8	45.5	48.0
Tarundl	27	34.5±24.1	41.8±21.7	5.9±1.3[a]	6.8±1.1	49.0	53.0
Miller	18	45.7±21.6	48.9±15.1	7.1±1.0	7.2±0.8	57.5	55.0
Piper	30	30.5±22.2	25.5±27.4	5.5±1.3[a]	6.8±1.0	45.0	52.5
Schomar	25	27.5±22.6	33.4±18.6	5.6±1.6[a]	6.9±1.3	45.5	54.0
Hangover	18	43.4±17.2	53.5±9.7	6.3±1.9[a]	7.6±1.2	50.0	59.0
Riley	18	40.7±18.0	47.9±11.6	5.8±1.2[a]	7.0±1.1	47.0	54.0
Bonanza	18	37.5±15.7[a]	49.9±14.3	7.3±1.0	7.6±0.9	58.0	59.0
Macmillan	30	47.1±18.6	42.9±20.2	6.0±1.1[a]	7.2±0.8	49.0	55.5
Saltspring	30	33.6±23.5	28.6±25.8	5.7±1.1[a]	6.6±1.1	44.0	51.5
South Bay	30	39.0±18.5	33.9±20.9	5.6±1.5[a]	7.0±1.2	45.5	54.5
Overall mean Average		38.0	38.6	6.0	6.9	48.5[b]	53.7

[a] $P<0.05$, t-test.

[b] $P<0.001$, Paired Difference t-test.

4.3 Effects of Sand on Coho Emergence Success

In the egg incubation study, coho fry emergence commenced on April 14 and was concluded by May 23 (Fig. 9). A total of 598 fry emerged from the 3300 eggs planted. This included 366, 141, 63, and 28 fry that emerged from the 9, 14, 28, and 39% sand mixtures, respectively. One of the 39% sand replicates had an early emergence of 148 premature sac fry and consequently it was excluded from any further analysis.

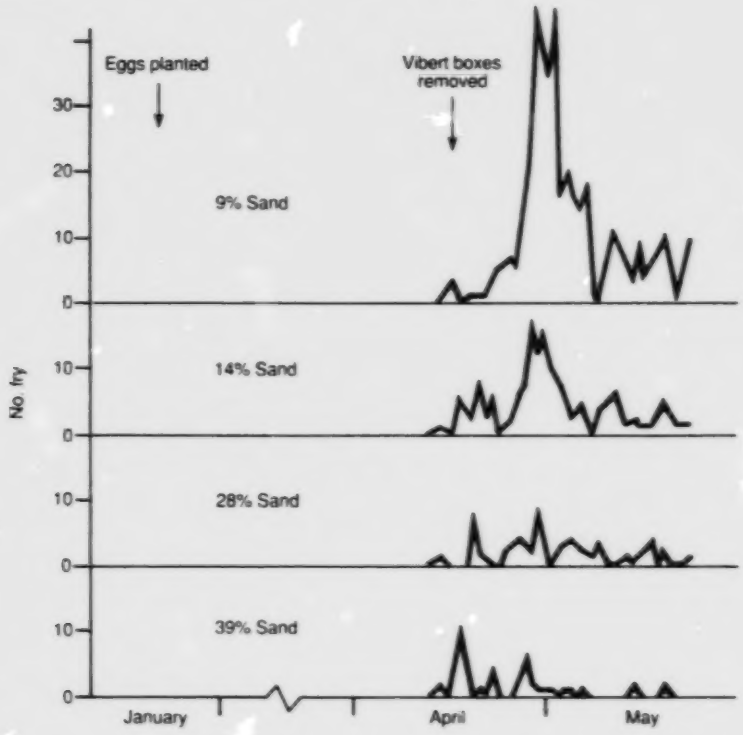


FIGURE 9. Coho fry emergence patterns in relation to four different concentrations of sand (particles <3.36 mm) in upwelling-type egg incubation boxes.

Coho survival from the eyed stage to emergence declined significantly with increased sand concentration, averaging 41% in the 9% sand mixture and 16, 7, and 5% in the 14, 28, and 39% sand mixtures, respectively (Table 10). Similar inverse relationships between salmonid egg or alevin survivals and increasing sand concentrations have been reported many times before (e.g., Bjornn 1968; Koski 1975; Phillips *et al.* 1975, Cederholm *et al.* 1981; Tagart 1984), although the survivals reported in previous experiments are generally higher than those reported here. Possible reasons for the variation include differences in egg and alevin size, and thus sensitivity to water quality or entombment. More likely reasons are differences in the experimental design (i.e., upwelling vs. downwelling incubation boxes) and sand-gravel mixtures used.

Dissolved oxygen concentrations and water flows were monitored regularly throughout the study and rarely appeared low enough to cause significant mortality. Over the course of the study, D.O. concentrations in the water flowing both in and out of each incubation chamber averaged 10.5 mg/L (range 9-12 mg/L). Subsurface measurements were an average of 1.7 (39% sand)- 2.1 mg/L (14% sand) lower than surface measurements, but with no clear-cut relationship to sand concentration. The lowest intragravel D.O. level recorded in each sand-gravel mixture was 5 mg/L in the 9% (May 17 and 19) and 14% (May 9) sand mixtures, and 6 mg/L in the 28% (May 17) and 39% (May 9) sand mixtures.

TABLE 10. Effects of different sand concentrations (particles <3.36 mm in diameter) includes fines on coho hatching and emergence success in upwelling-type egg incubation boxes

% sand conc. tested	Replicate no.	%Survival to hatching Vibert box	%Survival to emergence in incubation box	Estimated % alevin surv. to emergence	No.degree days(c°) to 50% emergence	Mean fork length()
	1	95	40.3		508	
9	2	74	19.7		508	
	3	0	62.0		519	38.0±1.4
		56.3±49.9	40.7±21.1	72.3	511.7±6.3	(N=380)
	1	98	10.7		503	
14	2	36	7.0		503	
	3	5	29.3		486	37.4±1.4
		46.3±47.4	15.7±12.0	33.9	497.3±9.8	(N=120)
	1	90	12.7		538	
28	2	100	3.7		481	
	3	100	4.7		444	37.0±1.6
		96.7±5.8	7.0±4.9	7.2	487.7±47.4	(N=53)
	1	97	3.3		387	
39	2	99	6.0		469	
	3	100	48.3		422	36.0±2.2
		98.7±1.5	4.7±1.9	4.8	426.0±41.1	(N=26)

[a] Mean value ±1SD.

[b] All premature sac fry data excluded in further calculations.

Survival to hatching in the Vibert boxes (Table 10) indicate that while there were occasional drops in water quality during the experiment, they occurred primarily in the boxes with the lowest sand concentrations (9 and 14%), and only then in the compartments with the highest emergence success. In the 9% sand boxes, for example, Vibert box survival was nil in the compartment with the lowest sand (4%) and the highest emergence (62%). Likewise, the lowest Vibert box survival in the 14% sand was recorded in the chamber with least actual sand (7.1%) and the highest emergence (29.3%). By comparison, in the incubation boxes with the highest sand concentrations (28 and 39%), survival to hatching in Vibert boxes was uniformly high (90-100%).

The Vibert box data indicate that in substrates with very little sand or fine-sized sediment, variations in subsurface water flow patterns may result in pockets of stagnant water forming, as water takes the route of least resistance. In such cases, low concentrations of sand (<10%) may have a beneficial effect on egg survival to hatching, by "damping out" the flow variability in highly permeable substrates. Bjornn (1968) reported similar results for recently hatched alevins, where consistently higher percentages of chinook and steelhead fry emerged from troughs with 12% sand (particles 0-6

mm approximately), compared to those with no sand.

When adjusted according to survival to hatching in the Vibert boxes, alevin survival to emergence showed proportionately much greater declines in survival than from the egg stage to emergence, dropping from 72.3% survival in 9% sand to 33.9, 7.2, and 4.8% survival in 14, 28, and 39% sand, respectively (Table 10). Since intragravel flows and D.O. concentrations appeared to be adequate, especially in the two highest sand concentrations, presumably most of the apparent mortality was due to fry being entombed when the interstitial environment was clogged with sand and fine-sized material. In the 28% sand-gravel mixture, sand occupies almost all of the available pore space between gravel particles. At 39% most of the gravel in the incubation chambers was supported by sand, i.e., the mixture was gravelly sand, not sandy gravel.

Average fry size was reduced significantly at higher sand concentrations, from 38.0 mm fork length in the low sand mixture to 36.0 mm in the high sand mixture (t-tests, $P<0.05$, Table 10), further suggesting that large fry suffer higher entombment rates. At higher sand concentrations, there was also a slight but significant decrease (ANOVA, $P<0.05$) in the number of degree days between planting the eggs and 50% emergence. Again the results were not unexpected; similar increases in the incidence of earlier emergence, prematurity, and decreased fry size at higher sand concentrations have been shown before in field (Koski 1975, Cederholm and Salo 1979, Tagart 1984) and laboratory studies (Phillips *et al.* 1975).

In the only other trough study on coho fry emergence, Phillips *et al.* (1975) recorded a 64% drop in alevin survival between 10 and 40% sand, or about the same net change in alevin survival recorded in this study. Absolute survivals, however, tended to be much lower in the present study; moreover, the decline in survival at intermediate sand concentrations was also sharper (Fig. 10). This suggests that there may be substantial variation in the sensitivity of different coho stocks to higher sand concentrations, particularly during the alevin stage when relatively small differences in cross-sectional head areas or body shape could have a major effect on the ability of alevins to move through gravel (Taylor and McPhail 1985a, 1985b). One major problem with comparing the results of this study with those of Phillips *et al.* (1975), is that the latter study used a maximum gravel size of 32 mm in diameter compared to 63 mm in this study. Depending on how sediment >32 mm in diameter affects the way smaller sediment packs together, the amount of intersticial space actually lost to sand in this study may have been greater than indicated. To be fully comparable, further tests are needed using gravel mixtures identical to those used elsewhere. Alternatively, different fish stocks could also be tested simultaneously.

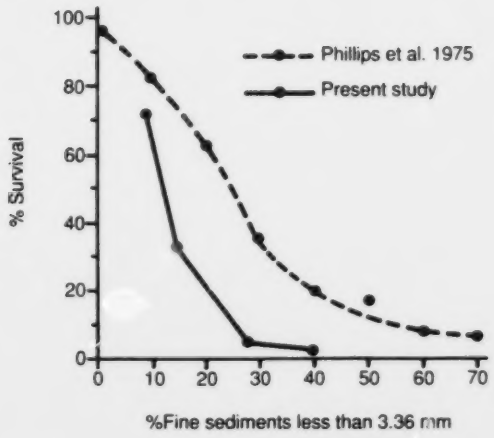


FIGURE 10. Coho alevin survival to emergence at different sand concentrations in this study and a study by Phillips *et al.* (1975).

5 CONCLUSIONS

The results of this study indicate that mass wasting and logging cause significant increases in fine sediment levels and gravel scouring in streams on the Queen Charlotte Islands. Of the two, increased sedimentation probably has the greatest overall impact, mainly because it affects low-gradient stream sections used by pink and chum salmon, the two most abundant salmon species on the Charlottes. Gravel scouring is probably not a major problem in low-gradient streams, but can be a chronic problem in torrented stream reaches used by species like chum and coho salmon, steelhead and cutthroat trout, and Dolly Varden char. While poor egg to fry survivals due to scouring may result in such streams being underseeded, with the exception of chum salmon all other species are usually limited more by the amount of over-winter cover available. As evidenced in this study, heavily aggraded low-gradient stream sections can suffer catastrophic egg losses due to scouring, but this probably only occurs during severe storms with a recurrence interval greater than 2 years.

Logging alone increases the level of fine sediments in streams as much or more than mass wasting upstream. This suggests that the cumulative impacts of other sediment sources associated with timber harvesting — road building, road runoff, gullying, an accumulation of small slides, surface erosion — can be as great or greater than those caused by a single conspicuous event like a debris torrent. That fine sediment levels are not substantially higher in logged streams with extensive mass wasting upstream is probably due to increases in gravel scouring associated with large-scale changes in channel morphology. Further increases in the amount of fine sediment present are therefore offset by increased gravel scouring in the most severely affected streams where logging occurs together with mass wasting upstream.

The decline in coho egg to fry survival due to mass wasting and/or logging-related increases in sediment levels in Queen Charlotte streams is estimated at 15-20%. This represents a substantial decline in natural egg survivals (possibly down to 6-11%) if survivals in Queen Charlotte streams are similar to those documented before logging at Carnation Creek on Vancouver Island (23-36%., average 26%). Further study is required to determine what the natural survival rates are for each major species, and what the sensitivity of each major species is to higher sediment levels. This is especially true of pink and chum salmon since these are the species most likely to be limited by declining egg to fry survivals. Although further testing is needed, results of the egg incubation experiments in this study suggest there may be considerable variability in the sensitivity of different fish stocks to fine and sand-sized sediment levels.

In stream reaches directly affected by debris torrents, estimated egg losses attributed to scouring for chum and coho salmon (the two major salmon species using torrented streams) were as high as 50 and 30%, respectively, after the first half of an uneventful winter (mean scour depth 25 cm), and 90 and 80%, respectively, near the end of winter (mean scour depth 35 cm). Since fine sediment levels in spawning areas of torrented stream reaches were as low as those recorded in undisturbed streams, obviously scouring and not sedimentation is the main factor governing egg to fry survival rates in these streams, provided fine sediments are not simply being salted out into lower strata. In the absence of LOD, debris-torrented stream reaches on the Queen Charlotte Islands contain few of the hydraulic controls necessary to store sediments and stabilize bed movements. Unless stable LOD placements are re-estabilished, excess scouring will probably remain a constant factor limiting fry production until most of the gravel present is either carried out of the stream or armoured with a protective layer of large boulders. If no further mass wasting occurs, eventually all excess gravel may be gone and parts of the stream may end up being sediment poor.

Excessive scouring appears to be a persistent, long-term problem in streams directly affected by mass wasting, as does sedimentation in downstream reaches. Most of the mass wasting affecting the streams included in the gravel scour study occurred 5 years before sampling was initiated and the streams affected were still highly unstable. Similarly, of the 20 stream reaches sampled for gravel that were located downstream of mass wasting events, 10 were affected three to four winters previously in 1978, 7 were affected seven to eight winters previously in 1974, and two were affected by mass wasting events initiated in the 1960's.

The long-term prognosis for cleaning and stabilizing bed materials in streams affected by mass wasting hinges strongly on the way the riparian zone is managed for LOD (Bryant 1983; Martin *et al.* 1986). Just as reductions in instream LOD reduce the amount of winter cover available for juvenile fish, so the number of

sediment storage sites are reduced. On the Queen Charlotte Islands, blow-down problems are sufficiently acute to warrant streamside prescriptions that permit logging to the stream edge. This practice aids in preventing bank damage, but it effectively removes the only source of natural debris to the channel. With rotational periods on the order of 70 years , it is questionable whether there will ever be enough debris to provide the instream stability and clean gravel conditions under which Queen Charlotte Islands fish stocks have evolved. In the absence of buffer strips that provide a constant source of LOD over time, intentionally putting LOD back into stream channels may be the only feasible alternative for managers to promote habitat recovery.

As important as LOD is in determining the quality of the spawning and rearing habitat present in streams, good debris management is not the whole answer for all streams. For some streams, irrespective of the amount of LOD present, if the amount of coarse and fine sediments entering streams exceeds the ability of LOD to store sediments or buffer its downstream movement, channel alterations will result. As stream sections approach their maxiumum carrying capacity for gravel, either because of increased mass wasting or decreased stable sediment storage sites, at some point even small additional inputs of gravel may trigger a second phase of infilling and channel broadening as banks start eroding and new channels start forming (see Roberts 1984). Thus streamside management prescriptions are not the only solution. Highly unstable areas like the Queen Charlotte Islands require not only effective streamside management plans, but also consideration of upstream or sideslope conditions to reduce surface erosion and mass wasting at its source.

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